Reading for this week: Chap. 6.2, 6.3, 6.5, 6.7
Homework #2 (posted on website) due Oct. 17
Reading for next week: Chap. 6.8, 7.5 and 7.6
Chap. 6 from Russell et al. book posted also.
Both cover shocks.

Solar wind and IMF

Parker’s model for solar wind

Back to original HD equations (ignore Lorentz force)
\[ \rho \frac{dv}{dt} = -\nabla p + F_{\parallel} \] no explicit time dependence and only radial variations
\[ \rho v \frac{dv}{dr} = -\frac{dp}{dr} - \rho GM_s / r^3 \]
Include continuity (spherical geometry!)
\[ (1/r^2) d(pvr^2) / dr = 0 \]
Assume isothermal
\[ \frac{dp}{dr} = 2kT \frac{dn}{dr} \]
\[ \frac{1}{r^2} \frac{d}{dr} \left( \frac{v^2}{2} - \frac{2kT}{m} \right) = \frac{4kT}{mr} \frac{GM_s}{r^2} \]

What do solutions look like?

- Four classes of solutions
  1. Initially flow is subsonic, reaches a maximum less than \( c_s \) at \( r_{cr} \), decreases monotonically
  2. Initially flow is subsonic, reaches sound speed at \( r_{cr} \), becomes supersonic
  3. Initially flow is supersonic, decreases to reaches sound speed at \( r_{cr} \), continues subsonic
  4. Initially flow is supersonic, reaches supersonic minimum at \( r_{cr} \), then increases speed

What do solutions look like?

- Look at limiting cases.
  - RHS = 0 for coronal temperatures
  - \( T_c = GM_m / 4R \) with \( R \) the radius of coronal base
  - \( T_c = 6 \times 10^6 \) °K
- for \( T < T_c \), RHS negative for \( R_c < r < r_{cr} \)
  - \( r_{cr} / R_c = T_c / T \)
  - RHS positive for \( r_{cr} < r < \infty \)

\[ \frac{1}{v} \frac{dv}{dr} \left( v^2 - 2kT / m \right) = \frac{4kT}{mr} \frac{GM_s}{r^2} \]

1. \( dv / dr = 0 \); \( v \) is maximum or minimum. \( dv/dr \) changes sign across \( r_{cr} \), but
\[ v^2 - 2kT / m = v^2 - c_s^2 \] does not change sign.
flow is either supersonic or subsonic everywhere

2. \( v^2 = c_s^2 \) at \( r_{cr} \)
then \( v \) either increases or decreases monotonically
What do solutions look like?

Four classes of solutions:

1. Initially flow is subsonic, reaches a maximum less than \( c_s \) at \( r_{cr} \), decreases monotonically
2. Initially flow is subsonic, reaches sound speed at \( r_{cr} \), becomes supersonic
3. Initially flow is supersonic, decreases to reaches sound speed at \( r_{cr} \), continues subsonic
4. Initially flow is supersonic, reaches supersonic minimum at \( r_{cr} \), then increases speed

Look at boundary conditions:

Look at 1 & 2:
At large \( r \), ignore gravity term.
For 1, \( \frac{1}{v} \frac{dv}{dr} (-2kT/m) = \frac{4kT}{mr} \) continuity equation gives finite \( n \) at large \( r \)

Parker's Solar Wind Model

Where is \( r_{cr} \)? Simple Parker says \(~6 R_s\)

Solar wind solutions for various coronal temperatures

(Hundhausen, 1972)

De Laval nozzle

\[
-\rho v^2 (dr)/(dr) + \frac{1}{2} v^2 - c_s^2 \frac{dx}{dr} = \frac{T}{\rho} \frac{dA}{dr} \]

(3)

Parker solution

\[
\frac{1}{v} \frac{dv}{dr} (v^2 - 2kT/m) = \frac{4kT}{mr}
\]

Look at 2 (subsonic becoming supersonic):

As \( r \to \infty \), \( \frac{1}{v} \frac{dv}{dr} (v^2 = \frac{4kT}{mr} = \frac{4kT}{mr} \)

\[
\frac{dv}{dr} = \frac{2kT}{mr} \Rightarrow v^2 - \frac{4kT}{m} \ln r
\]

This gives \( n \sim 1/(r^2 (\ln r)^{1/2}) \) and pressure goes to zero

Parker's exact solution

\[
(v^2 - v_c^2) - v_c^2 \ln \left( \frac{v^2}{v_c^2} \right) = 4v_c^2 \ln \left( \frac{r}{r_c} \right) + 2GM \left( \frac{1}{r} - \frac{1}{r_c} \right)
\]

with \( v_c = 2kT/m \)
De Laval nozzle

\[ p v A = \text{constant} \]
\[ p v d v / dr = -dp / dr \]
\[ \frac{v^2 - c_s^2}{v} d v / dr = \frac{T}{\rho} \]

A is cross-sectional area of nozzle

Same behavior: For \( dA/dr < 0 \), if flow is supersonic at minimum in \( A \), will accelerate as nozzle area increases

So solar wind has 'effective de Laval nozzle' due to gravity and continuity

How realistic? What have we ignored?

- Structures on many scales (temporal and spatial)
- Magnetic field!
- Hydrodynamics requires collisional (short mean free path)
- Different sources
- Temperature

Stereo data on solar wind


Example of plasma and magnetic field data from the Ulysses SWICS, SWOOPS, and MAG instruments. (a) The magnetic flux measuring in situ, (b) plasma beta, (c) solar wind proton speed, (d) oxygen charge state ratio, and (e) solar wind proton density.
**Solar wind magnetic field**

Solar atmosphere is high conductivity- flux ‘frozen-in’

In photosphere/ lower corona, fields frozen in fluid rotate with the sun
Often region inside ~2Rs is ‘source surface’ for magnetic field

In outer corona, plasma (solar wind) carries magnetic field outward with it

**Plasma beta - who pushes whom?**

![Graph showing plasma beta values](http://c2h2.ifa.hawaii.edu/Pages/Outreach/resources_videos.php)

Aschwanden et al., 2001

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**Near Poles**

Treat field as radial. Use conservation of magnetic flux:

\[
B_r A = B_0 A_0
\]

\[
A = 4\pi r^2 \Rightarrow A_0 = 4\pi r_0^2
\]

\[
B_r 4\pi r^2 = B_0 4\pi r_0^2
\]

\[
B_r = B_0 \left( \frac{r}{r_0} \right)
\]
Lower latitudes

- Treat lower boundary (source surface) initially radial magnetic field
- 'Footpoint' rotates with sun, $\omega_S$
- Imagine garden hose

As sun rotates and solar wind expands get longitudinal component of $B$

$$B_y = -B \left( \frac{\omega}{r} \right)$$

Using $B_r = B \left( \frac{\omega}{r} \right)$

$$B_y = -B \left( \frac{\omega}{r} \right) \frac{\omega}{v_w} = -B \left( \frac{\omega}{r} \right) \frac{v_s}{v_w}$$

- Resulting field called 'Parker spiral'

Parker angle (garden hose angle)

What is the average angle the equatorial magnetic field makes with the radial vector to the sun?

$$\omega = 2.87 \times 10^6 \text{ s}^{-1}$$

At Earth (1 AU $\approx 1.50 \times 10^8$ km), the co-rotation velocity is $\omega_r = 429$ km/s

$$V_w \approx 400-450 \text{ km/s}$$

So angle of IMF $\approx 45^\circ$

Parker spiral

More realistic versions

Average IMF Strength and Direction

<table>
<thead>
<tr>
<th>Planet</th>
<th>Angle</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>21°</td>
<td>35 nT</td>
</tr>
<tr>
<td>Earth</td>
<td>45°</td>
<td>7 nT</td>
</tr>
<tr>
<td>Mars</td>
<td>56°</td>
<td>4 nT</td>
</tr>
<tr>
<td>Jupiter</td>
<td>80°</td>
<td>1 nT</td>
</tr>
<tr>
<td>Neptune</td>
<td>88°</td>
<td>0.2 nT</td>
</tr>
</tbody>
</table>
Output from the Hakama-da-Akasofu-Fry model (HAFv.2) showing the spiral of the interplanetary magnetic field (IMF) – the Parker Spiral – distorted by propagating CMEs. The locations of the inner planets are shown; the spacing of the spokes is an indication of the solar wind velocity. Image courtesy of Geophysical Institute, University of Alaska, Fairbanks, Alaska USA. http://www.helio-vo.eu/science.php

Structure of the Interplanetary Magnetic Field

New 3-d view of magnetic field structure, with distorted current sheet crossing ecliptic

(http://pluto.space.swri.edu/image/glossary/IMF.html)

Heliospheric current sheet

Solar wind structure: Fast, slow and intermittent


Adding start of current minimum

Solar Wind Velocity: Ulysses measurements

Comparing polar to equatorial

Average properties

(McComas et al., JGR, 105, 10419-10433, 2000)

Knipp, 2011
Fast/slow solar wind

Origin of fast wind: Coronal holes

Ion Composition data

Knipp, 2011
This figure shows the composition of a large event which was measured by ACE-SWICS on May 3 and compares it to standard solar wind composition (labeled slow solar wind). The Fe and O charge state show that the CME plasma is composed of a very hot (about 2.5-3 million K) and a very cold (less than 0.3 million K) component.

Solar wind observations from the Proton Monitor on the SOHO spacecraft indicate that the solar wind at this time was likely a coronal hole-associated high speed stream. Dominant observed charge states for Fe are +9 and +10, in excellent agreement with the few previous measurements in coronal hole-associated solar wind flows in the ecliptic plane made by instruments on the ISEE and ULYSSES spacecraft. These charge state distributions correspond to a coronal “freezing-in” temperature of about $1.1x10^6$ K. Interestingly, the dominant Fe charge states observed by the ULYSSES/SWICS instrument at large heliographic latitudes are consistently +10 and +11, higher by about 1 charge state unit than the in-ecliptic measurements.

Temperature differences of protons and alphas: evidence for heating processes in corona

Differential flow of protons and heavy ions: evidence for heating processes in corona

From NASA’s SDO Atmospheric Imagine Assembly (AIA) instrument
V~30 miles per second; periods of 150 to 550 seconds
McIntosh et al, Nature, 2011

Evidence for Alfvén waves in corona

Solar Probe Plus

SCIENCE OBJECTIVES:

Determine the structure and dynamics of the magnetic fields at the sources of the solar wind:
  a. How does the magnetic field in the solar wind source regions connect to the photosphere and the heliosphere?
  b. How do the observed structures in the corona evolve into the solar wind?
  c. Is the source of the solar wind steady or intermittent?

Trace the flow of the energy that heats the solar corona and accelerates the solar wind:
  a. How is energy from the lower solar atmosphere transferred to and dissipated in the corona?
  b. What coronal processes shape the non-equilibrium velocity distributions observed throughout the heliosphere?
  c. How do the processes in the corona affect the properties of the solar wind in the heliosphere?

Determine what mechanisms accelerate and transport energetic particles:
  a. What are the roles of shocks, reconnection, waves, and turbulence in the acceleration of energetic particles?
  b. What are the seed populations and physical conditions necessary for energetic particle acceleration?
  c. How are energetic particles transported radially and across latitudes from the corona to the heliosphere?

Explore dusty plasma phenomena and their influence on the solar wind and energetic particle formation:
  a. What is the dust environment of the inner heliosphere?
  b. What is the origin and composition of dust in the inner heliosphere?
  c. What is the nature of dust-plasma interactions and how does dust modify the spacecraft environment close to the Sun?